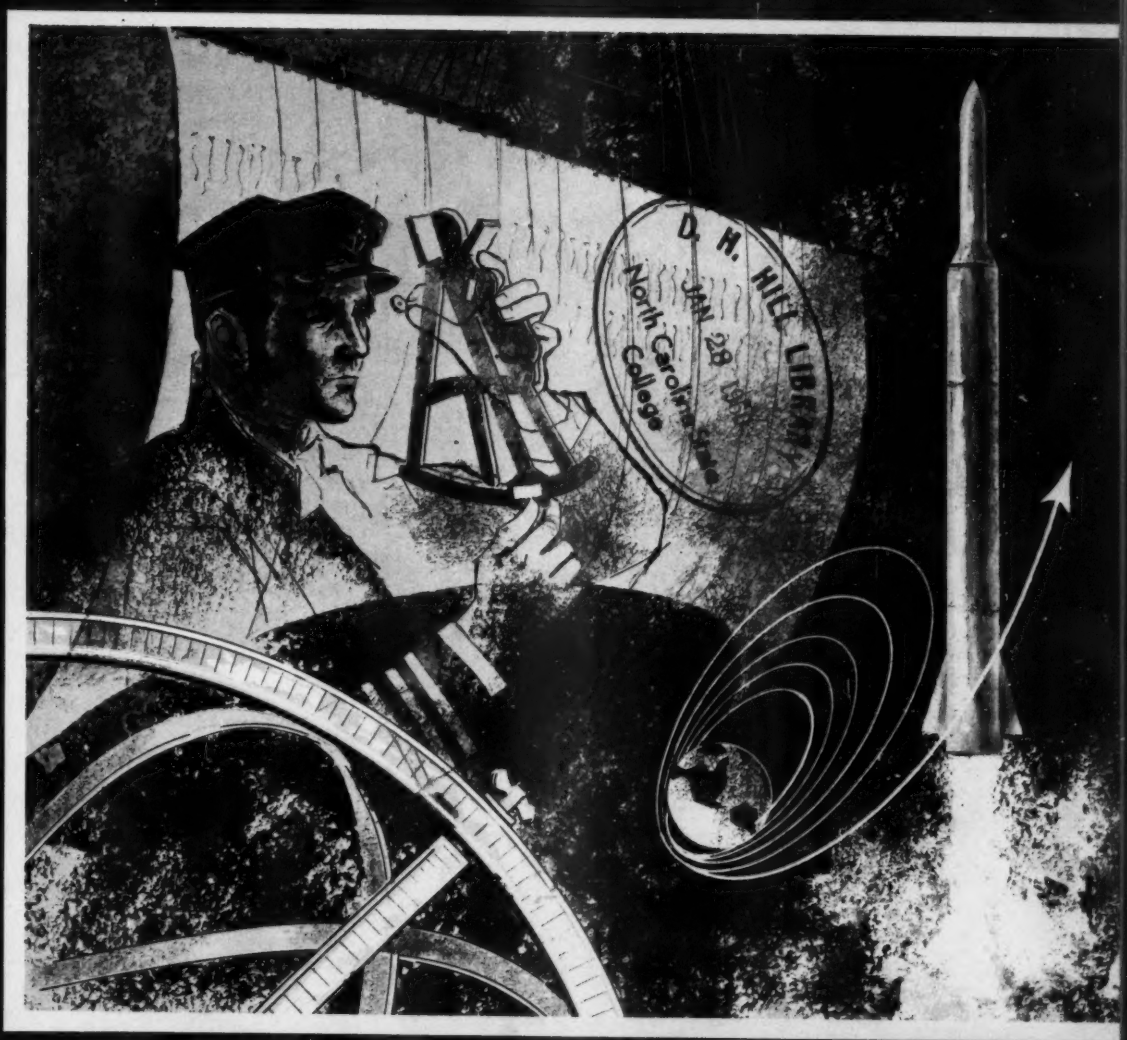
RAYTHEON

ELECTRONIC PROGRESS



In this issue:

ELECTRONIC PROGRESS

Volume IV January-February 1960 Number 4

RAYTHEON

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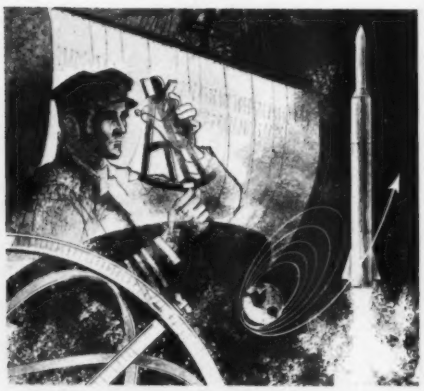

Our cover drawing depicts the advance in navigation aids from the sextant and armillary sphere, used to orient the sailor of old, to the complex systems demanded by a modern rocket venturing into space.

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Calendar

ENGINEERING SEMINARS

Seminars will be held every other Tuesday at 4:45 P.M. in various laboratory cafeterias. Security clearance will be required as indicated. Personnel who do not hold picture badges should consult their security officers for attendance arrangements.

"Proprietary Information — The Engineer's Responsibility"	Jan. 19	Unclassified
E. J. Gorn, Law Department	Wayland Lab Cafeteria	
To be announced	Feb. 2	
"Low-Noise Microwave Amplifiers"	Feb. 16	Unclassified
W. Beauregard, Wayland Lab.; I. Goldstein, Bedford Lab.; C. Shafer, Research Div.	Wayland Lab Cafeteria	
"The Generation of Super Power at Microwave Frequencies"	March 1	Confidential
W. C. Brown, Microwave & Power Tube Div.	Wayland Lab Cafeteria	

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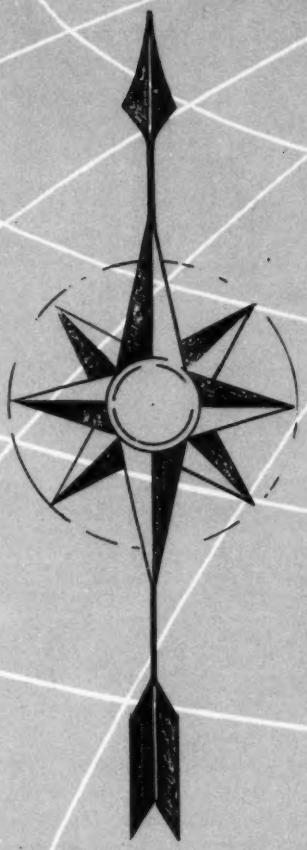
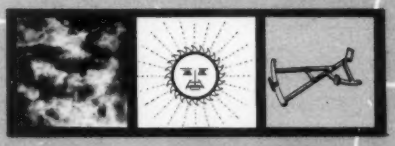
NAVIGATION

... new challenges for an old art



N. P. Cedrone
Government Equipment Division



NAVIGATION, in terms of the traditional seafaring definition, is the art of determining the position of a vehicle at any time and of conducting it safely from one place to another.

Navigation methods and instruments had their origin and development in connection with sea travel. Undoubtedly, the first developments were associated with travel within sight of land wherein position and direction were given through contact with earth objects, an aspect of navigation which is known as piloting. There is evidence that the earliest sea travelers were not timid about moving out of sight of land, getting their sailing directions from the celestial bodies — the sun, planets and stars — the form of navigation which today is known as Celestial Navigation or Nautical Astronomy. They got further information about direction through the association of winds having specific characteristics with definite directions. This, of course, was before the discovery of the north-seeking property of the lodestone.

Dead Reckoning Navigation, a corrupted abbreviation of deduced reckoning, was also practiced in an early age. It is the art of estimating present position from information on course and speed made good from the last known position.

The arrival of air travel, with its greater speeds and varying altitudes, introduced new problems into the art of navigation. While the traditional navigation methods were adapted successfully to aircraft navigation, additional assistance was required and supplied through the development of Radio Navigation.

Recent years have seen considerable effort applied to the development of inertial systems of navigation. These have been made feasible through the availability of useful inertial components.

Reference to the definition of navigation will show that safety is a significant consideration. Thus, collateral aspects of navigation are methods of preventing collisions of vehicles, of keeping track of vehicles and collectively controlling them, of bringing ships into mooring without collision, and of landing aircraft on runways without accidents.

This paper presents a brief review of the development of present systems of navigation and discusses trends for the future, primarily from the point of view of instrumentation.

Piloting

Piloting is the art of navigating in coastal and inland waters and the approaches to land through the observation of landmarks and the ocean bottom. Positions are fixed as the point or region of intersection of two or more lines-of-position, on which the vehicle is assumed to lie simultaneously, determined from measurements on landmarks of known position. These lines-of-position are straight lines when generated by a bearing measurement on a single object or by a range (defined as the alignment of two known objects). When the distance to a landmark is measured the lines-of-position are circles with center at the landmark and radius equal to the measured distance.

A range may be determined by eye. Relative bearings are measured by means of a pelorus or dumb compass, illustrated in Figure 1. A more recent development is the self-synchronous alidade bearing repeater, which enables a true bearing to be obtained easily.

Distances may be determined by means of optical rangefinders or by the measurement through a sextant of the elevation angle of a landmark of known height.

Radio aids have extended the use of piloting to greater distances than possible with visual piloting, and to all-weather operation. Radio bearings are obtained by means of direction finders aboard the vehicle. These determine the direction of radiation from a radiating source of known land position, such as a radio beacon or radio station. Bearings are also obtained from shore-based direction finders operating on radio transmissions from the vehicle, information being communicated back to the vehicle.

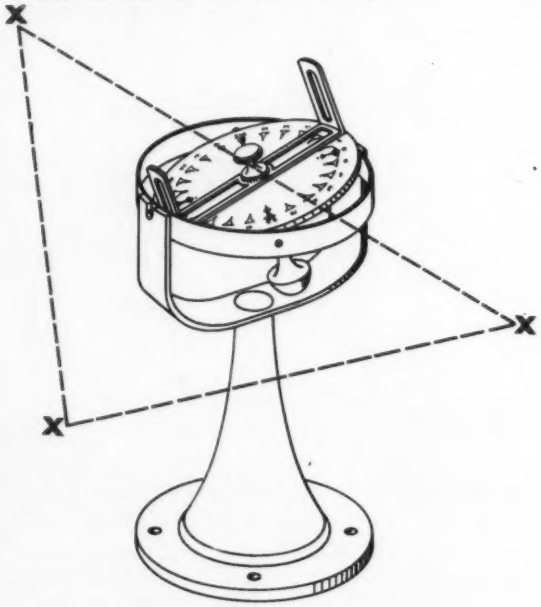


Figure 1

Radio ranges consisting of radiation restricted to a sector are also used, but mostly in connection with aircraft navigation.

Distance may be determined by measuring the time of transit of radiation from the vehicle to a natural land reflector and back, such as in a radar, or the transit time to a radiator or beacon which responds to the interrogation of a radio signal from the vehicle.

Simultaneous transmission of radio and sound from a shore station to the vehicle is also used to measure distance. The interval between the arrival of the radio and the sound signal serves as a measure of the sound transit time and thus distance.

Radar is also used to present a plan view of the land area which can be compared with a chart for the purposes of position location.

The depth of water under a ship is another factor involved in piloting. It is important to the safety of the vessel and may also be used to determine approximate position when a chart showing water depths is available.

The lead and line is the simplest instrument for obtaining soundings. It was and still is used in navigating coastal waters and the approaches to land. Information on the nature of the sea bottom, another factor useful to navigation, is also obtained by means of analyzing specimens adhering to the bottom of the lead.

The line is the oldest navigation instrument. It was first mentioned by Herodotus, a Greek historian, but there is evidence that it existed long before his time. The simple lead and line was supplanted by the sounding machine attributable to Lord Kelvin. It consists of a reel-wound line with an element at the end of the line which is reeled to the bottom and records in some fashion the depth. The most recent and fast depth-finding instrument is the sonic depth finder such as the Fathometer® which is coming into widespread use for small as well as large craft.

Just as bottom clearance is important to a marine craft, so also is terrain clearance or altitude important to the navigation of an aircraft. A discussion of such altimeters is presented in an accompanying article.

Dead Reckoning

Dead reckoning consists in the determination of present position from a known position by integrating the measured velocity components along reference directions. In the case of earth navigation the reference directions are East-West (E-W) and North-South (N-S). The integration formulas are:

$$L = L_o + \int_o^t \frac{V_{NS}}{R}\, dt$$

$$\lambda = \lambda_0 + \int_0^t \frac{V_{EW}}{R \cos L} dt$$

where L is latitude, λ is longitude, V_{NS} and V_{EW} are the North-South and East-West components of velocity, R is the radius of the earth, t is time, and the subscript zero indicates initial or known values. Since the North-South direction is at every point tangential to a great circle, there is a constant relationship between distance and change in latitude. However, the ratio between distance traveled East-West and change in longitude is proportional to the cosine of latitude. It is evident that the essentials of dead reckoning are first, to have a known starting point; second, to know the speed of the vehicle; and third, to know the reference directions along which the velocity must be resolved.

Consider the velocity. The first recorded instrument for measuring velocity was the "hodometer" or "way measurer" described in 14 B.C. by Vitruvius, a famous Roman architect and engineer. It was attached to the hull of a ship and consisted of a paddle wheel about four feet in diameter which actuated a train of three gears. The last gear operated a gate which caused a pebble to drop into a box at each revolution of the gear. The count of pebbles over a time measured by a sand hourglass gave a measure of the distance sailed. Leonardo da Vinci referred to the hodometer as inaccurate because the water adjacent to the hull tended to follow the ship. This instrument might be considered the forerunner of the taffrail or patent log (a small propeller towed through the water whose rate of turn is proportional to the speed of the ship).

The knotted log line came into use sometime in the sixteenth century. It consisted of a piece of wood to which was attached a line knotted at known intervals. In operation this log was thrown over the side and the line allowed to run freely through the fingers. The rate at which the knots passed the fingers was recorded as the speed of the vessel in "knots" or nautical miles per hour, time being measured by a special hourglass. It is a natural surmise that the use of "knot" to mean nautical miles per hour derived from the foregoing.

Today, ship's speed is measured by the pit-log (pitometer log) which makes use of a Pitot tube projected outside the ship's hull. This method is used normally under maneuvering conditions when the velocity information is fed automatically to the dead reckoning tracer which provides a continuous graphical record of the ship's position in relation to the starting point.

For steady steaming, velocity is obtained from the shaft revolution rate of the screw. This is a more accurate method, allowing an accuracy to one-tenth of a knot in calm water over a thirty knot range.

Bowditch . . . Author of "The New American Practical Navigator."

Aircraft air speed is determined by means of the Pitot-static tube in a manner similar to the pit-log method. The static tube measures atmospheric pressure at altitude, and the open-ended Pitot tube measures the head on pressure which varies with speed. Ground speed is calculated from air speed and the aircraft drift angle which is measured by means of drift sights using optical sightings of a ground object.

More recently, in keeping with the increased requirements of accuracy, accelerometers have come into use. These are inertial components which measure linear acceleration along the reference axis of the instrument. Successive integrations of acceleration give in turn velocity and distance traveled. These instruments can be made extremely accurate with appropriate calibration; however, they drift, so that accuracy degenerates with time.

Another recent development for the measurement of aircraft velocity is the Doppler radar. The Doppler shift is a measure of the component of velocity along the antenna heading. Thus, measurements from three non-coplanar antennas determine the aircraft velocity in the antenna reference system. The Doppler velocity information fluctuates quite rapidly and is a poor short term measure of velocity; however, the long term average of the Doppler information is quite accurate.

These complementary characteristics of Doppler and inertial information have been used to advantage in the Doppler-Inertial Navigation system, an example of which is the B-58 navigation system. In this, the inertial and Doppler information are added after appropriate filtering to give velocity information which reflects the short-term accuracy of the inertial data and the long-term accuracy of the Doppler.

Consider now reference directions which are essential to Dead Reckoning. In the case of earth travel these are East-West and North-South. Centuries B.C. the Egyptians established these two direction lines. They made use of the rise and set of the sun and the apparently fixed direction of Polaris, the North Star. In ancient times directions were also identified with the distinctive characteristics of the winds, even as is done today.

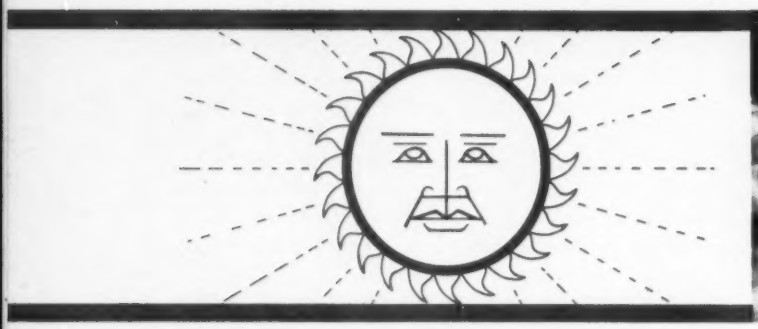
The discovery, usually attributed to the Chinese, that lodestone supported by a board floating on water points in the northerly direction gave birth to the magnetic compass which has served navigation long but not always faithfully.

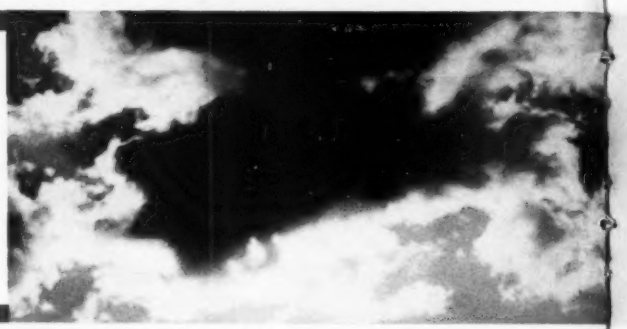
The gyrocompass, although its possibility had been known for some time, became a practical instrument following the patents of H. A. Kaemfe in Germany in 1908, E. A. Sperry in the U.S.A. in 1911 and S. G. Brown in England in 1916. The principle of the gyroscope, a term invented by Foucalt, had been known for a considerable time and had its first practical use long before — the Chinese being credited with the first scientific toy, the spinning top.

The gyrocompass is essentially a free gryoscope with a pendulous element suspended in such a way that a torque is applied to the gyro when the spin axis is not in the plane of the local meridian, causing a precession of the spin axis about the meridian. This motion is damped so that the spin axis finally comes to rest and tends to stay in the meridian plane in a horizontal position. When the axis of spin is in the meridian plane the pendulous element does not apply a torque component normal to this axis and there is no precession. The gyrocompass has a period of about 84 minutes.

Because of weight and long stabilization time, initial designs of the gyrocompass were not suited for airborne use. However, units have been developed which are being used in aircraft and small boats. For airborne use the gyromagnetic compass was developed. This consists of a gyro whose direction is slaved to the magnetic compass heading. The combination of the two serves to correct, on the one hand, the drift tendency of the directional gyroscope and, on the other, to filter out the short term fluctuations of the magnetic compass.

Both the magnetic and the gyro-compass degenerate in accuracy in the region of the poles.





Celestial Navigation

With travel beyond the sight of land ancient sailors had to depend in great part on the observations of celestial bodies for navigation information. Initially, directional information alone was available. It was known early, for example, that the star Polaris had a relatively fixed direction. With the growth of mathematics and astronomy positional information also became available and celestial navigation developed to its present form.

The celestial navigation method basically consists in measuring the altitude (that is, the angle between the line of sight and the local horizontal plane) of several celestial bodies — moon, planets or stars. The locus of points on the surface of the earth from which the altitude of a given celestial body is the same at a given instant is a "circle of equal altitudes." The intersection of two such circles fixes the position. Usually an estimate of position is close enough to enable a proper choice from the two points of intersection. The celestial objects are selected such that the circles of equal altitude intersect at approximately right angles. This is done to minimize the positional error corresponding to a measurement error. It is common, again in the interests of accuracy, to make three measurements and use the center of the triangle of intersection as an estimate of position.

Thus, the elements necessary for celestial navigation are measured altitudes, requiring a knowledge of the local vertical or horizontal plane, and an instrument for measuring angles; a clock keeping a common reference time; nautical almanacs and calculations. When position is known approximately an estimate is

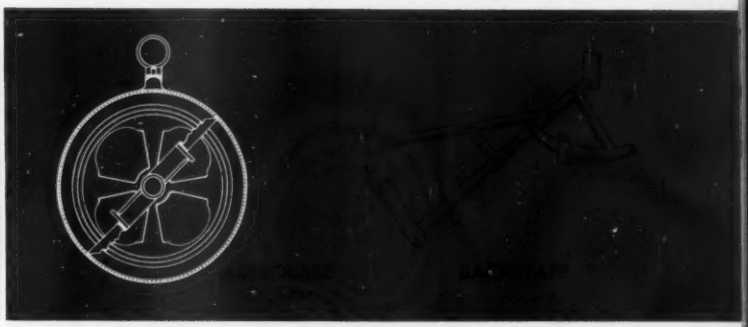
used in the calculations. These are reduced to a simple routine and answers are given as corrections to the assumed position.

Azimuth information also is obtained which, when compared with the measured azimuth, can be used to check the compass.

When the celestial body is a star its direction in terms of an inertial reference system is almost exactly the same, no matter from what point on earth or at which time the measurement is made. This, of course, is due to the tremendous distance of the stars when compared to the major dimension of the earth's orbit in the solar system. However, because of the rotation of the earth, the direction of the local horizontal in terms of an inertial reference is continuously rotating. Thus, the altitude of a star from any given place depends on the time of day, unless the star lies on the extension of the earth's axis of rotation when it is fixed. Such a star is Polaris, whose altitude from any fixed place varies by at most one degree.

If the object is the sun its direction changes not only with the time of day but with the season of the year. If the object is another planet or the moon then the direction will vary even more because of the motion of the planets and the moon. However, all these motions are known. If the time is known these changes in direction can be taken into account through pertinent information recorded in nautical almanacs.

The astrolabe was the first instrument used in the determination of the altitude of celestial bodies. It is attributed to Hipparchus about 130 B.C. and is considered to be the first known scientific instrument. Its use in navigation was perfected by the Arabs. It consisted of a circular disc about 18 inches in diameter, graduated in degrees from 0 to 360, and provided with an alidade or index pivoted at the center of the



disc. This index was provided with peep sights by means of which it could be aligned with the celestial body. It required a three-man team to operate: one to hold the disc by a ring pivoted from the zero, one to sight, and one to read and record.

A more accurate instrument consisted of the fore staff, also known as the cross staff, Jacob's staff and the balestilha, probably invented by the Portuguese or Spaniards and first described in 1557. Next came the quadrant and the back staff which remained the standard navigator's observing instrument for about 200 years.

In 1731 John Hadley, a fellow of the "Royal Society" of England, developed the octant, which later became the sextant, and which has remained the manual instrument for measuring the altitude of celestial bodies.

By the use of mirrors the image of the celestial body is adjusted to fall on the horizon towards which the instrument is sighted. The altitude is then read from the vernier scale. For aircraft use the bubble sextant was developed, in which a bubble level is used to create an artificial horizon.

There are under development, if not already in operational use, automatic star trackers for use with the modern aircraft which will continuously measure the navigation parameters of a star, or other celestial body, with considerable accuracy.

The measurement of altitude requires a knowledge of the local vertical or horizontal. At sea this information is obtained by sighting on the horizon, corrections being made for systematic errors due to such things as height above sea level of point of observation. Airborne radar methods for determining the horizontal direction have also been suggested.

Local vertical can be readily determined by means of a pendulous element which lines up with the direction of local gravity. An example of such a system is the bubble sextant used with aircraft. In this case the bubble represents the pendulous element. Pendulous methods are subject to serious error due to horizontal accelerations of the carrying vehicle. However, there exist so-called Schuler-tuned systems (named after the man who first pointed out the possibilities) which are insensitive to horizontal accelerations. Such a pendulous system has a period equal to that of a simple pendulum having a length equal to the radius of the earth plus the altitude of the point of suspension. For present day aircraft altitudes the period is approximately 84 minutes. It is impractical to achieve a simple or physical pendulum with such a period but it can be simulated through feedback systems. Such systems tend to be unstable. However, a velocity input into the system dampens out the instability and results in a very accurate vertical. An example is the Hustler Navigation System which contains a vertical system which is approximately Schuler-tuned and makes use of the Raytheon Doppler Radar velocity information for stabilization.

Another factor necessary to celestial navigation is a time reference. Greenwich Civil (Mean) time is the universal reference for navigation purposes. This time in marine navigation is kept track of by means of an accurate clock called a chronometer. Such a clock was first completed in 1735 by John Harrison, an English clockmaker. The accuracy of his timepieces was such that on an 81-day trip in 1761, the clock used was in error five seconds at the end of the trip. Our modern chronometers can do better than this and can be synchronized by means of radio broadcasts from time standard stations, such as WWV.

For the more accurate requirements that may exist in the future, there are atomic clocks for airborne use which can keep time with an accuracy of better than one part in ten to the tenth power. These are being developed to the point where orders-of-magnitude greater accuracy will be possible.

The development of the sextant and the chronometer by Hadley and Harrison marked the end of the prescientific age of navigation. The coming of the automatic star tracker and the atomic clock may well mark the beginning of the space age of navigation.

Radio Navigation

The number of radio navigation aids are too numerous to detail here but they fall into a relatively few categories characterized by the lines of position — which, for the most part, are approximately straight, circular or hyperbolic when related to the surface of the earth.

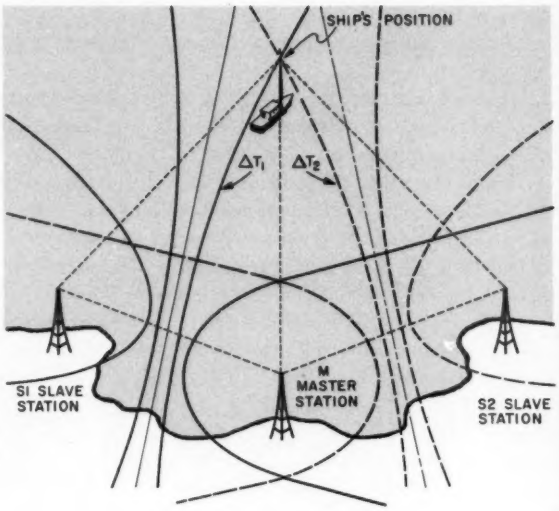


Figure 2

Within the first category, radial systems, are direction finders used in connection with radio beacons or radio stations. Here the straight line of position is the bearing line between the direction finder and the radiation source.

It was not long after the development of the radio that such radio direction finding equipment was used aboard ship. It was not until 1936 that it was first used in U. S. aircraft. Of the first category also are radio ranges which define a narrow angular sector from a transmitter of known position. These have been in use with aircraft since 1929. The original patent on the device was issued in 1907 to O. Schiller, a German.

Still another example of bearing measuring equipment is "Sonne," which was developed by the Germans and used in the Second World War. The English having discovered its existence also made use of the same setup to navigate into Germany, but they renamed the system "Consol." There are quite a few others, including the CAA range; Post Office Position Indicator (POPI), a development undertaken by the British Post Office in 1941; and Navaglobe, developed in the U. S.

Equipment falling in the second category, circular systems, in which a circular line of position is determined through a measurement of distance to a known point, came into use during the Second World War. It consisted of a radar-beacon system in which the radar interrogated and the beacon responded. The interval between interrogation and response was a

measure of the range. An example of such a system is Shoran, developed during the war as an aid to blind bombing.

Some systems measured both range and bearing, thus generating a straight and a circular line of position whose intersection determined a fix. Tacan (Tactical Air Navigation), developed for the armed services of the United States in the period 1949 to 1952, is such a system. Another example is Navajo, an extension of the Navaglobe mentioned above.

In the third category are those systems which make use of hyperbolic line of position. These are called, naturally, hyperbolic systems. One of the original and important examples of the above is Loran (Long Range Navigation), developed during the Second World War by the Radiation Laboratory. The system operates as follows: a transmitter, known as the master station, generates an rf pulse which is received by the navigating vessel. This pulse is also used to trigger a similar pulse from a second station known as the slave station, some distance away. This second pulse is also picked up by the navigation receiver. The time interval between the arrivals of the two pulses is a measure of the difference of the distances from the two stations. The locus of all points from which the time interval is the same is a hyperbola whose foci are at the two stations. Loran charts show families of these hyperbolic lines of position identified by appropriate time interval values for the pairs of transmitters. The intersection of two hyperbolic lines of position will determine a fix. The same master station may be used with two slave stations, the different transmissions being identified by appropriate coding. Figure 2 illustrates a typical setup.

The first of the hyperbolic types was the Gee system, very similar to Loran, using pulses and a master and two slave stations. It was proposed in England in 1937 and put into operation in Great Britain in 1942.

Another hyperbolic system is Decca. It was first proposed in the United States before the war, but when no interest was shown in the system by the United States, it was brought to Great Britain where the Decca Navigation Company of London developed it. It differs from the pulse systems in that it uses continuous wave (CW) transmission and uses phase comparison for time measurements. It tends to be more accurate than pulse systems, however; "cycle matching" of the rf signal within the pulses give such pulse systems comparable accuracy.

Development work is still going on in the hyperbolic system field, an example being Omega, using very low frequency transmissions.

Other radio aids relate to the safety of aircraft in the approaches to airports and the safe landing. Examples are surveillance radars, Ground Control Approach systems and Instrument Landing Systems which contribute to the solution of the landing problem when visual methods are impossible.

Inertial Methods

The spherical coordinate system of reference identifies uniquely the points on the surface of a sphere by means of two angles. These angles can be simply related to the latitude and longitude coordinates used in earth navigation. It is thus possible to locate a point on the earth by measuring the angles between the locally determined vertical and reference axes whose directions remain fixed in inertial space. The vertical direction can be determined by means of the pendulous elements discussed previously, and the inertial frame of reference can be maintained aboard the vehicle by means of free gyros. The change in local vertical due to the earth's spin can be adjusted automatically through timing mechanisms.

Present inertial systems are essentially dead reckoning systems using gyros with servo systems to maintain reference directions; accelerometers to sense gravity and vehicular accelerations; integrators to determine reference for the integrations and to account for earth spin; and a computer to convert measured information into interim information necessary to operate the system and into navigation information such as present position in latitude and longitude, ground velocity and track, distance traveled, and distance and course to destination. Local vertical is not necessarily determined by pendulous elements but may be kept track of through data or a physical reference generated by the dead reckoning process.

The major difficulty with systems operating under the foregoing principle is that the gyros and accelerometers drift with time. These instruments are being improved with significantly reduced drift rates so that operation over longer periods with adequate accuracy is being achieved. Another factor against present airborne use is the size and weight of accurate instrumentation but this also is being improved. Inertial systems for earth navigation approach the ideal, since they are self-contained, non radiating and invulnerable to jamming. The airborne experimental Spire system developed at M.I.T., SINS (Shipboard Inertial Navigation System), and the system developed for the Navajo missile and used by the USS *Nautilus* and the USS *Skate* in their polar trips, are examples of inertial systems.

Other Methods

Any measurable qualities which can be identified more or less uniquely with the points on the earth can be used for navigation. A more academic than practical example of this is supplied by the earth's magnetic

field whose declination or variation (the angle between magnetic and true north) and inclination (the angle of dip below the horizontal) is a function of position. By measuring the variation by means of a magnetic compass and a gyrocompass, and the dip by means of a magnetic inclinometer, the local position in latitude and longitude may be determined by reference to a map on which these quantities or their equivalent have been plotted. In space, electron density, direction and intensity of radiations and so on could be used to identify regions and directions.

Conclusion

The systems described in the foregoing are concerned essentially with present day earth travel. Today's military and commercial requirements of greater speed of travel and greater accuracy are applying continual pressure to improve these methods and make them more automatic. Tomorrow's interplanetary travel and the somewhat later space travel outside our solar system will require the solution of successively more complex problems.

The solution of these problems undoubtedly will result in part from the evolution of techniques now in use and in part from revolutionary new methods based on concepts which may be new to us even today.

The basic navigation problems are the same, the determination of present position in some chosen frame of reference and the determination of the course necessary to attain the navigation objective. In addition, it may be desirable to have collateral information such as distance traveled from start, distance and time to objective, fuel required, fuel available, what areas in space to avoid as dangerous to the travelers, and other information whose need is not readily apparent now.

The methods for basic navigation must fall into one of two categories: the first, in which a place is identified or fixed by local measurements of parameters or spatial properties which are uniquely identified with each place over the region of interest known in terms of some known reference system; and the second, dead reckoning, in which present position is known through the integration of travel from a position known in the frame of reference being used.

Reference directions are available through bearing lines to the stars which are so remote that for all practical purposes lines of sight to a given star from over a large region are parallel. Problems involved are the identification of a given star and the generation of lines of sight.

Star trackers existing and under development will be available to track the line of sight of celestial bodies through radiation. It may also be possible that other types of radiation may be identified with specified directions in inertial space and thus be useful to navigation.

Gyroscopes may also be used to set up and maintain a reference direction in inertial space. The major difficulty, of course, is the gyro drift. This is being improved more and more in the conventional types by reducing bearing friction with fluid bearings, obtaining better balance and improving the pickoff methods. In addition, new methods such as electrostatic flotation are being developed.

A revolutionary approach now in its infancy makes use of the gyroscope properties of molecules and atoms. It is hoped thereby to get much greater accuracy than with the present conventional gyro.

The measurement of position poses a much more difficult problem. The intersection of the lines of sight from three non-co-linear stars is impractical, since stellar distances are so tremendous that even infinitesimal errors in bearing would result in large position errors.

In the vicinity of systems such as our solar system it may be practical to measure bearings and distances from objects whose relative motions are known. Assistance could be obtained here by use of radio aids located on the celestial bodies or anchored in space in stable, known orbits.

Sensing the direction and magnitude of the local gravity field could be, under some circumstances, useful, but it would be a complicated function of position. In free space its usefulness is doubtful. Accelerometers which would measure such a field are being continually improved both as to sensitivity and accuracy. The problem of sorting out the vehicular accelerations remains.

Position could also, of course, be obtained by dead-reckoning by the double integration of accelerometer measurements, or by the integration of velocity. Measurements of change in Doppler shift of radiation from stars is being considered as a means of determining velocity.

Dead reckoning appears to be the most promising method of navigation. Improvement in accuracy of instrumentation would make possible greater intervals of travel between necessary checks on position or fixes.

When and how navigation systems will reach the full maturity of unlimited space travel is at the moment a mystery but it will make a tremendously interesting story, with perhaps a surprise ending or two.

AIRCRAFT ALTIMETERS

E. J. Sheldon
Government Equipment Division

AIRCRAFT altitude may be measured with respect to different references; hence, altimeters are classed by the reference used. Absolute or terrain clearance altimeters indicate the actual height above the terrain. Relative altimeters indicate the height with respect to an arbitrary ground reference plane, most commonly Mean Sea Level (MSL). Assume an aircraft flying 9000 feet above a plateau that is itself 1000 feet higher than MSL (Figure 1). An absolute altimeter shows a height of 9000 feet, while a relative altimeter indicates a reading of 10,000 feet. Both altimeters read correctly, illustrating the application of the two generic types.

The type of instrument to be used depends on the end use of the information. For air traffic control, relative altitude is used to maintain vertical separation of in-flight aircraft. For flight safety, terrain clearance altitude is used, especially during the landing approach.

Pressure Altimeter

The barometric type is the most commonly used altimeter. It measures altitude in terms of atmospheric pressure, which is a function of height. This function can be derived from the hydrostatic equation and the equation of state for an ideal gas. Air follows this equation to a good degree of approximation.

Hydrostatic Equation $$\frac{\partial P}{\partial h} = -\rho g \qquad (1a)$$

Equation of state $$P = \rho \frac{R}{m} T \qquad (1b)$$

where P is the pressure; h is the altitude; ρ is the air density; g is the gravitational acceleration; R is the universal gas constant; m is the molecular weight; T is the absolute temperature.

Combining the above equations and solving for pressure, we get

$$P = P_o \exp\left(-\int_o^h \frac{gmdh}{RT}\right) \qquad (1c)$$

This equation gives the vertical distribution of pressure in the atmosphere, within the accuracy of observation.

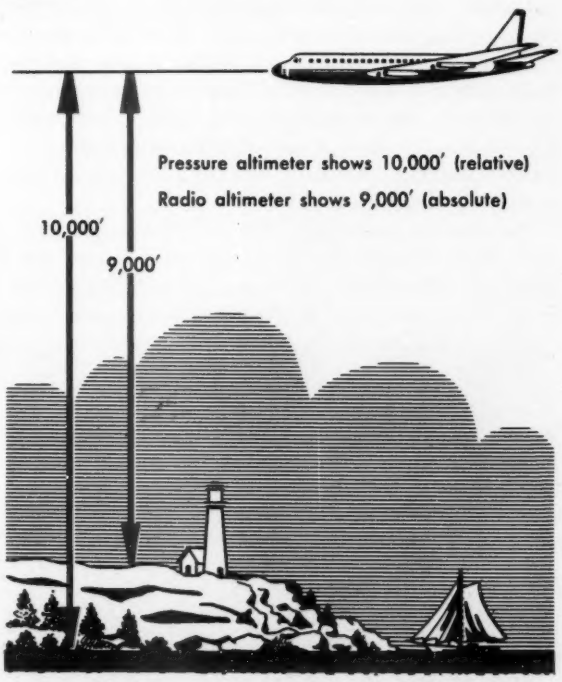


Figure 1

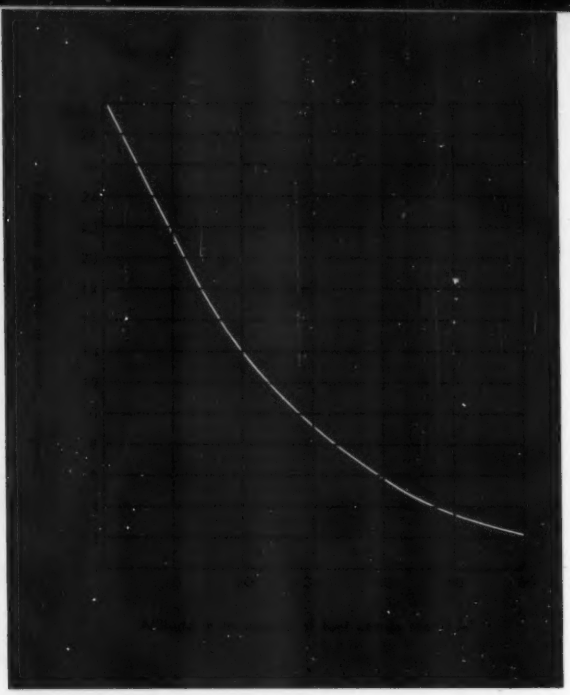


Figure 2

Barometric altimeters measure the pressure only; therefore, to calibrate the altimeter, it is necessary to assume average values of temperature, water vapor content, sea level pressure, etc. Based on these average values, a standard pressure-altitude curve can be made. This curve is shown in Figure 2. The altimeter indication of height can be inaccurate due to errors in measuring the pressure and to deviations of the pressure from normal. At high speeds it becomes very difficult to measure the static pressure of the outside air. The accuracy is a function of many factors, such as velocity and angle of attack. At speeds near mach 1, the pressure effect of the shock wave can make the barometric altimeter useless.

The most obvious source of error for barometric altimeters is the variation of atmospheric pressure with time. An adjustment is available which allows setting the proper atmospheric pressure (reduced to sea level) into the altimeter. Elaborate procedures for setting the altimeter have been worked out. For landing, and in the vicinity of the airport, the altimeter is set for the local pressure at the airport, using information radioed from the tower. Terrain clearance altimeters are more suited to the landing operation, but many planes are not equipped with them; therefore, accurate setting of the barometric altimeter must be used.

For enroute operation in the United States, the aircraft is required to fly at a certain altitude, depending on direction of flight and the flight rules — under visual flight rules (VFR) and an eastward heading (0 to 179° magnetic): at odd thousands (of feet) plus 500; for a westward heading: even thousands plus 500. Under instrument flight rules (IFR) they fly at odd thousands for eastward and even thousands for westward. The altimeter setting is corrected to the pressure of a nearby station every 100 miles. Planes approaching each other can have altitude settings from locations as much as 200 miles apart. Surveys have shown that the differences between these settings (for ground stations 200 miles apart) are greater than 300 feet more than one-third of the time. Because of the differences encountered when setting altimeters, etc., a proposal was made that all aircraft flying enroute would maintain altitude according to the same setting (29.92 inches of mercury). This proposal was not accepted because it meant a loss of air space, since the lowest expected atmospheric pressure, at the ground, would determine the minimum "pressure" altitude, and much of the time, this pressure level would be thousands of feet off the ground. However, on transoceanic flights, the standard pressure setting must be used, since local sea level pressure is not known.

Radio Altimeters

Radio altimeters measure the time delay of a transmitted radio signal beamed to ground and reflected back from the earth. Pulse and FM/CW radio altimeters measure the same basic parameter, although they employ different techniques.

The pulse radio altimeter simultaneously transmits a pulse of radio frequency energy and starts a timing circuit (Figure 3). An interval of time (Δt) later, the altimeter receives the reflected pulse and stops the timing circuit. The time delay, Δt, is expressed as

$$\Delta t = \frac{2h}{c} \qquad (2)$$

where h is the height above ground and c is the velocity of propagation. Because this is a linear relationship, the time delay can easily be converted to feet and displayed on a meter, counter, or oscilloscope.

The controlling limitation here is the length of the transmitted pulse. The time span occupied by a 0.1 microsecond pulse corresponds to a height of approximately 50 feet, and if conventional pulse radar techniques are used, this height is the minimum that can be measured. However, pulse radar techniques have advanced greatly in the last few years, and the use of leading edge trackers and/or millimicrosecond pulses will eventually make the pulse radio altimeter competitive with the FM/CW radio altimeter for low altitude work.

The pulse altimeter is better suited for accurate high-altitude operation than the FM/CW altimeter. The FM/CW altimeter generally has an accuracy proportional (e.g. 5%) to indicated altitude, whereas

the pulse altimeter tends to have a "fixed accuracy" (e.g. 50 feet) at all altitudes.

While the pulse altimeter operates in the time domain, the FM/CW altimeter operates in the frequency domain. An r-f transmitter is frequency modulated as a function of time, so that $F_t = F_o + f(t)$, where F_t is the instantaneous transmitted frequency, F_o is the nominal center frequency, and $f(t)$ is the instantaneous deviation. The signal received back from the earth is delayed by a time interval, Δt, equal to $2h/c$, just as in the case of the pulse altimeter. During the interval Δt, the transmitter frequency changes, and the received signal frequency, F_r, equals $F_o + f(t-\Delta t)$. When the two signals are mixed, the difference frequency becomes

$$\Delta f = f(t) - f(t - \Delta t) = F_A \quad . \quad (3)$$

If, as is generally the case, the change of frequency is small during the interval Δt, the difference frequency equals the derivative of frequency times Δt, or

$$F_A = \Delta t \frac{df(t)}{dt} = \Delta t\, f'(t) = \frac{2h}{c} f'(t) \quad . \quad (4)$$

In a radio altimeter, the variation of the transmitted frequency is known, and the characteristics of the difference frequency (a linear function of altitude) are used for altitude indication. In the Raytheon-designed AN/APN-22 Altimeter, the transmitter frequency is modulated by a triangular wave so that the derivatives of the upsweep and downsweep are positive and negative constants. The altitude signal, F_A, alternates between plus and minus (Figure 4). Because the AN/APN-22 uses a video system which does not distinguish between positive and negative frequencies, the altitude signal will be a constant frequency, since the discontinuity at the turn-around point is small enough to be neglected. This frequency, F_A, is measured by a cycle rate counter which develops a voltage proportional to frequency and, therefore, to altitude. The transmitter deviation in the AN/APN-22 is constant from 0 to 200 feet. Above 200 feet, the return signal frequency is held constant by a servo loop which varies the transmitter deviation. The transmitter deviation then becomes the function of altitude. By holding the return frequency constant, a much narrower band amplifier can be used, thereby improving the signal to noise ratio at high altitudes.

Unlike pulse altimeters, FM/CW altimeters are well-suited for measuring low altitudes, because the short time delays at low altitudes are converted to low frequencies which do not present serious operational problems. Below 200 feet the AN/APN-22 uses a constant deviation of 60 megacycles, with a modulation rate of 120 cps, or a period of 8.33 milliseconds. Because each upsweep and downsweep occurs in half this time, the frequency slope is

$$f'(t) = \frac{f}{t} = \frac{60(10^6)}{4.1(10^{-3})} \quad . \quad (5)$$

Substituting in Equation (4),

$$F_A = \frac{2h}{c} f'(t) = \frac{2h}{983(10^6)} \frac{60(10^6)}{4.1(10^{-3})}$$

where h equals 28.7 cycles per second, expressed in feet.

Because the AN/APN-22 uses a simple counter that quantizes the information, the output will be in approximately 4-foot increments $\left(\frac{120}{28.7} \text{ feet}\right)$. The counter registers one count for each four feet of altitude, and the theoretical indications will be 0, 4, 8 . . . 4n feet. For example, when a delay line is used that simulates nine feet of altitude the counter would always give two or three counts per sweep (depending on the rf phase). In practice, the ground return shows different rf phases (a quarter wave length at the transmitter frequency of 4300 mc is about 0.7 inch). The altimeter in a moving aircraft would tend to give one extra count on every fourth sweep, thereby indicating properly a nine-foot altitude.

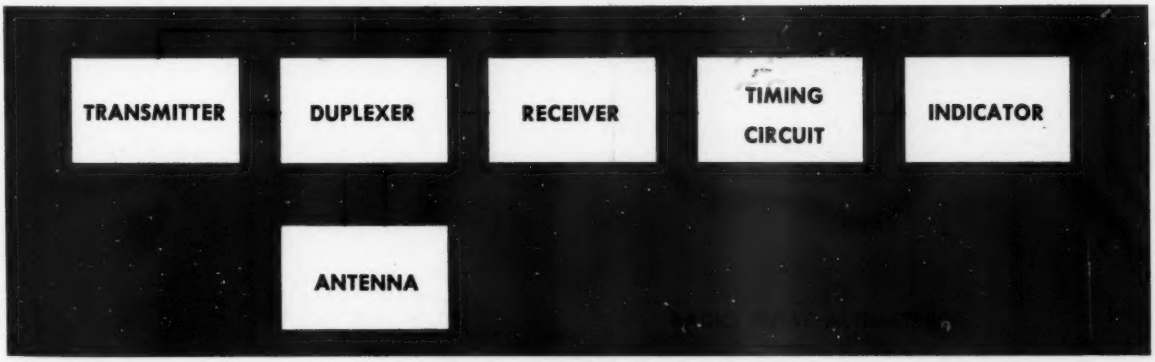


Figure 3

The FM/CW altimeter will work down to zero feet. However, there are some problems that affect accuracy at extremely low altitudes. Transmitter amplitude modulation, 400 cps pickup, residual range signals from aircraft protuberances, and Doppler return from moving aircraft parts all contribute false signals that affect altimeter accuracy.

Doppler return from ground presents another source of error. At extremely low altitudes, the effective Doppler frequency resulting from aircraft velocity can exceed the altitude frequency. If most of the signal return is from directly below, as over a runway, the radial component of Doppler is small and the error is negligible. When the terrain is rough, returns from off-boresight can be received (the beamwidth of the AN/APN-22 Altimeter is 60°), and if the Doppler frequency exceeds the altitude frequency, the equipment measures velocity rather than altitude.

Antenna beamwidth is a practical problem in both pulse and FM/CW altimeters. An altimeter is required to measure altitude despite pitch and roll. This could be done with a vertically stabilized narrow beam antenna, or one whose output is corrected by resolvers for pitch and roll. In either case, the antennas must be quite large and the added circuits impose weight, load, and power penalties. To reduce circuit complexities, yet assure a good beam-ground contact, radio altimeters generally use broadbeam antennas. Their small size and light weight are partially offset by the fact that targets many degrees off vertical affect system operation. These unwanted targets tend to give a higher altitude output (terrain bias error). Unfortunately, the terrain bias is not constant, resulting in a system error in the order of one per cent.

Other Height Finding Systems

Triangulation, both optical and electronic, is a practical altimeter technique. Optical triangulation is one of the most precise measuring methods used. Recording theodolites are used at most test installations as the primary reference for other altimeters. However, extensive installations are required, they are restricted to a given area, and they work only under conditions of good visibility.

Ground-based height finding radars measure altitude by measuring the distance to an aircraft and the angle of the antenna beam to the horizontal. Ground Controlled Approach (GCA) radars multiply the slant range by the sine of the antenna angle to find the altitude, and present the data on an E-scan (elevation versus range) indicator. Defense systems might use this type of radar to determine the altitude of the

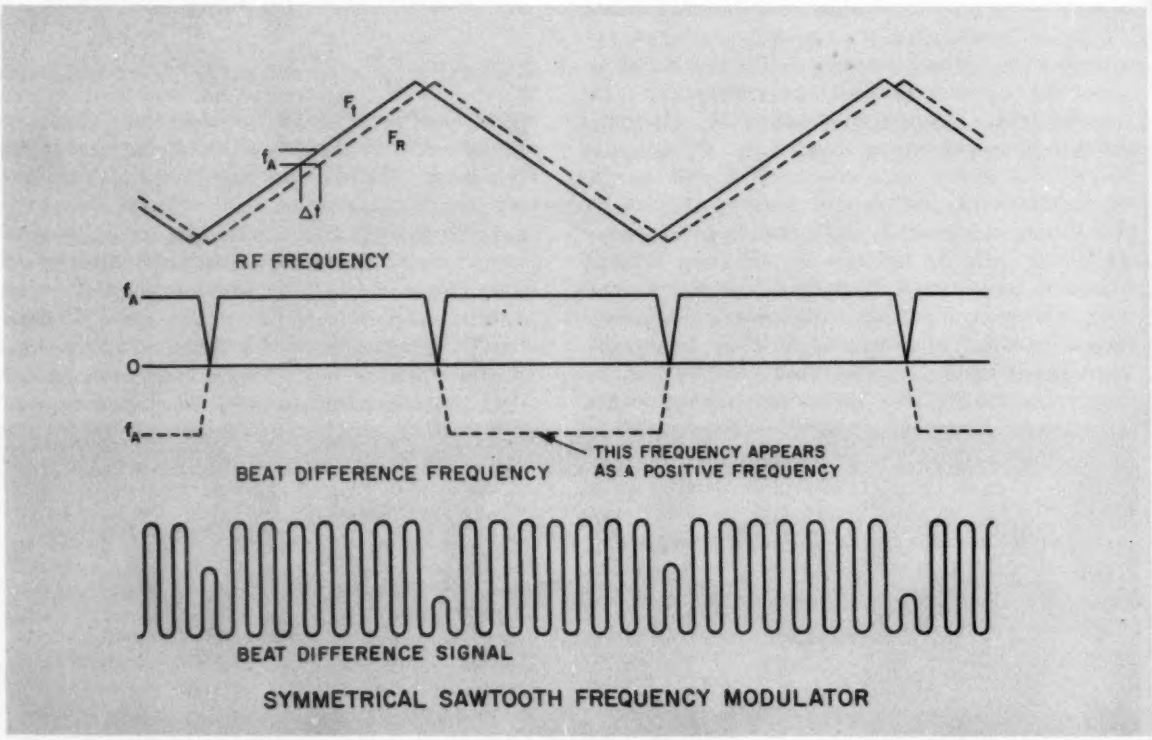


Figure 4

attacking force. Height finding radars are used in conjunction with azimuth-range radars, and are usually controlled by the latter.

In certain limited tactical situations, hovering aircraft such as helicopters and blimps might make contact with the surface — for instance, when towing a sonobuoy. The length of the cable can then be used as a measure of altitude.

Sonic altimeters operate in a fashion similar to radar altimeters, but measure the time delay of a sound wave transmitted through the air. Because of the high acoustic noise levels normally surrounding an aircraft, their use is restricted to low altitudes.

All the foregoing are practical altimeter devices. Altimeters can be built on other physical principles, but in the present state of the art, they do not provide better operation for any useful application. Capacitance altimeters determine altitude as a function of the capacity between the aircraft and the surface of the earth. They are limited to a useful range of about 100 feet. Gravity altimeters measure the force of gravity, which is a function of altitude. A one per cent change in gravity corresponds to a 25-mile change in altitude. Cosmic ray intensity varies as a function of altitude, and is more or less predictable from 0 to 65,000 feet. However, the barometric pressure is easier to use and more closely predictable over this range. Dropping an object and measuring the time it takes to reach the ground is also possible. At high altitude the object signals by a radio transmitter which stops when contact with the ground is made. At very low altitudes, the instant of impact can be determined visually.

The Future

With the advent of the space age, altimeters that will work on the moon and the planets, as well as on the earth, will soon be necessary. These space age altimeters will have performance requirements far exceeding the requirements for earth-bound altimeters. For a safe moon or planet landing, the altimeter will have to provide accurate altitude data from over 100 miles down to zero feet. For the first exploratory landings, radar altimeters will be used. In the far future, it is possible that exotic altimeters can be designed for specific planets, using unique planet features in the same way that the atmospheric types (barometric, sonic, and cosmic ray) have been utilized on earth.

Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

Name	*Field of Invention*
Herbert Bailey, Harold Brinson, John Nazarow	Sub-Miniature Holder
Robert J. Chamberlain	Dither Joining
Robert D. Corwin, Henry Maloney	Automatic Assembly Mechanism
Gerhard A. Flodberg	Assembly Machine
Peter Fowler, Austin King	Pulse Generator
Robert A. Fryklund	Vector Computer
Francis A. Gicca	Transistor Amplifiers
H. Gerald Gross	Heater Cathode System
Gilbert A. Horsman, Herbert C. Single	Fathometer Recorder
Pascal Levesque	Spacer for Getter Assembly
William H. Rymes	High Velocity Target Simulator
Melvyn A. Snyder	Scribe Etch for Pedestals
Herbert C. Single	Ghost Eliminator
Ross Wood	Quick Heating Cathode

NAVIGATION IN SPACE

C. Carruthers **Missile Systems Division**

Primitive man would have found navigating to a star no more difficult conceptually than piloting a log raft across a small lake. It would have been quite impossible for him to understand the motions of the celestial bodies, or to appreciate the invisible gravitational whirlpools that surround them. The modern earth-bound navigator, for all his superior knowledge, would if suddenly thrust into space, be only a little better off.

The stars which, when viewed from the earth's surface told position, now tell only attitude. A collision warning radar is impractical for it merely forecasts the occurrence of an inevitable event. Under certain conditions, thrust applied in the direction of motion slows the vehicle, while a retarding drag causes the vehicle to accelerate, in a seeming paradox to earth-bound experience. The course to be followed is no longer a great circle, but perhaps an elliptical spiral, or some sort of expanding cycloid depending on the motion of the viewing point. The earth is no longer a suitable inertial frame of reference, and the "true" equations of motion must relate to the "fixed stars." The forces of gravity cannot be contested directly by relatively feeble though ever persistent exotic propulsion systems. If the power source should involve a large solar reflector, then even the pressure exerted by a sunbeam must be considered. A human being could scarcely be an ideal space navigator, for he remembers far too much, far too imperfectly.

The purpose of the present article is to attempt to point out some of the problems of space navigation, and to explain some of the techniques for solving these problems.

NAVIGATION might be defined quite simply as the gathering and utilization of information necessary to effect an efficient transfer from one location to another. There are, however, subtle differences in navigational philosophies. For example, a course may be determined and all efforts expended toward making good a track over this course (as in flying a radio beam), or the course can be continually recomputed from the vehicle's instantaneous position (as in the case of an active homing missile). While the former view of space navigation is frequently taken in current literature, it is quite conceivable that the latter method would result in a considerable simplification of equipment.

In general, the primary information to be gathered for navigational purposes includes determination of: the vehicle's attitude (direction of heading) or orientation with respect to some reference direction, the vehicle's present location relative to some fixed point (starting point, terminal point, or arbitrary refer-

ence), and finally, the vehicle's velocity vector relative to its heading. In space, the sun and stars provide attitude information but require some sort of sighting device. While planets can also be used, their rapidly changing positions must be taken into consideration. Positional information is [illegible] more difficult to obtain and, in general, requires the direct measurement of at least one distance, either by radar device or by triangulation, using apparent planetary or solar disk sizes (or almanac and chronometer calculations from apparent planetary positions). Position can be calculated by integrating accelerometer readings twice with respect to time, but corrections must be made for operation under free-fall conditions, and these corrections are themselves a function of position. Velocity information is even more difficult to obtain directly. While several velocity-measuring devices will be discussed, it would seem, particularly during midcourse, that a navigational scheme should be chosen which is relatively insensitive to velocity error.

The Environment

To solve the navigational problem safely and efficiently, it will be necessary to have a thorough knowledge of the space environment. With the possible exception of local high-energy-radiation belts, the huge gravitational forces exerted by bodies in our solar system are by far the most significant features with which the space navigator must deal. The relative magnitudes of the gravitational potentials due to the sun and the earth are shown by the potential energy curve on this page. On this curve, potential energy is represented along the vertical axis and radial distance from the attracting mass along the horizontal axis. The slope of the curve at any point is a measure of the gravitational field at that point.

A somewhat over-simplified plot of the orbits of the earth's more immediate neighbors is given in Figure 1. To indicate their relative orbital rates it has been imagined that they all started at the same time from points along the lower axis. Ramps of various heights indicate that the orbital planes are inclined with respect to the earth's orbital plane (ecliptic).

It is a completely unexplained fact that the relative distances of the planets from the sun (shown to scale) can be approximated from Bode's Law, $[4 + 3\ (n - 1)]/10$, where n is a number representing the order of the planet counting away from the sun, and with the earth (n = 3) having an orbital radius equal to unity. The approximation is so good that the one exception, an unfilled orbit among the outer planets, is suspected of being the result of a celestial accident. The navigator who expects to take off from or land on a planet should note that in general its axis of rotation is inclined at some angle to its axis of orbital revolution. The surfaces of Venus and Mercury are far too well obscured to determine whether or not they are exceptions to this rule.

While the exact planetary motions are highly com-

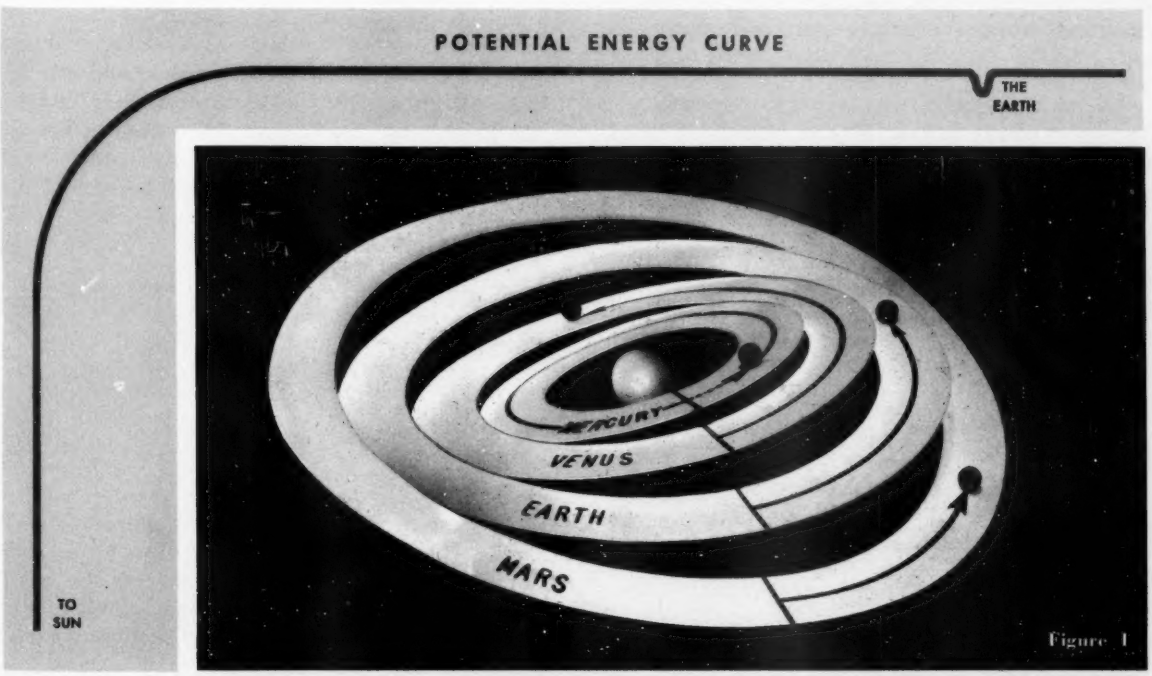


Figure 1

TABLE I — SOLAR SYSTEM DATA

	SUN	VENUS	EARTH	MARS
Mean Distance from the Sun (Statute Miles)		67.0×10^6	92.9×10^6	141.5×10^6
Mean Orbital Velocity (Feet/Second)		114,000	98,000	79,000
Sidereal Period (Days)		224.7	365.26	687
Eccentricity of Orbit		0.00681	0.0167	0.0933
Inclination of Orbit to the Plane of the Ecliptic (Degrees)		3.4	0	1.85
Inclination of Equatorial Plane to Orbital Plane (Degrees)	7.2 TO ECLIPTIC	NOT OBSERVABLE	23.45	25.2
Gravity at Surface (Feet/Second^2)	897	28.2	32.2	12.7
Escape Velocity at Surface (Feet/Second)	2,000,000	33,600	36,700	16,700
Sun's Gravity at Planet's Orbit (Feet/Second^2 and G)		0.0371 0.0011g	0.0194 0.0006g	0.0084 0.00026g
Solar Radiation Intensity (Kilowatts/Meter^2)		2.62	1.38	.59
Minimum and Maximum Disk Diameters as seen from the Earth (Milliradians)	9.0	0.047-0.29		0.018-0.084
Albedo (Surface Reflection Coefficient of Entire Planetary Disk)		0.59		0.15
Radial Distance from Center of Planet to Point Where Planetary Attraction Equals Solar Attraction (Miles)		105,000	160,000	80,000

plicated, they have been cataloged with considerable precision and are readily available in almanac form to the space navigator. Table I lists the approximate mean values of several of the more important physical quantities required for navigation.

It is certainly a fortuitous circumstance that the planets we are likely to visit first travel in orbital planes only slightly inclined to the ecliptic (Figure 1). If the angles were large, the energy and guidance requirements would both be much more severe.

Laws of Planetary Motion.

Early in the seventeenth century, after an intensive study of observed data, Kepler enunciated the following conclusions about the motions of the planets:

I. The orbit of a planet is an ellipse with the sun as a focus.

II. The area swept out by a radius from the sun to the planet is traversed at a constant rate.

III. The square of the time in which a planet traces out its orbit is proportional to the cube of its mean distance from the sun.

It should be remembered that Kepler's Laws apply to conservative central force fields involving only two bodies. With the restriction that the central body is many times more massive than the planetary body, the motion can be described in terms of a conic section, with the central body located at a focus. The general equation of a conic section with a focus at the origin (Figure 2) expressed in polar form is:

$$r = \frac{e\rho}{1 - e\cos\theta} \qquad (1)$$

where: r is the radius vector from the origin to the point P;

ρ is the distance from the origin to the directrix;

θ is the angle between the axis and the radius vector;

e is the eccentricity, which is the ratio of the length r to the perpendicular distance from the point P to the directrix.

The equation represents an ellipse when $e<1$. The total energy of a body in a conservative field (without propulsion) is a constant, and equal to the sum of kinetic and potential energies.

$$\text{T.E.} = \text{K.E.} + \text{P.E.} = \frac{1}{2}mv^2 - \frac{mk}{r} \qquad (2)$$

where $k = GM$, G being the gravitational constant and M the mass of the central body. The total energy may be expressed in terms of the eccentricity and of a constant, h, related to the angular momentum.

$$\text{T.E.} = \frac{m}{2}\frac{k^2}{h^2}(e^2 - 1) \qquad (3)$$

where h equals $rv \sin\phi$, ϕ being the angle between the radius vector r and the velocity vector v. It is interesting to note that for an ellipse ($e<1$), the total energy is negative. When $e = 1$ the total energy is zero and the path a parabola, closed only at infinity. Thus the conditions for escape from the central body are that $e \geq 1$, or that the total energy be equal to or

greater than zero. Equation (1) may be rewritten in terms of the physically more meaningful quantities h and k.

$$r = \frac{h^2}{k(1 - e\cos\theta)} \tag{4}$$

In the case of a circular orbit the radius is a constant, and equating the central forces:

$$\frac{mv^2}{r} = \frac{mk}{r^2} \tag{5}$$

which reduces to:

$$v = \sqrt{\frac{k}{r}} \tag{6}$$

which indicates that adding energy to go to an orbit of greater radius will result in a decrease in velocity.

The actual motions of a space vehicle will obey Kepler's Laws when the vehicle is in free fall (no propulsion) and when it is situated so that only the forces between two bodies need be considered. In the case of a vehicle using an amount of thrust very much smaller than the central gravitational forces, the motion will closely approximate free fall during any short portion of the trajectory.

Interplanetary Mission Phases

In simple form, navigation for a rocket flight from the earth to Mars would involve only the previously mentioned catalog of planetary information and a knowledge of the rocket's thrust characteristics. All that would seem necessary is to aim precisely, give the proper instructions to the inertial guidance, and demand sufficient accuracy from the components. Present practical experience with moon rockets, however, suggests that a considerable amount of terminal guidance would be required to achieve an orbit about Mars. Thus far we have been assuming a high-thrust rocket and, hence, a rather direct and calculable ballistic trajectory. It is unlikely that such a rocket would be used, except for the smallest probes, because of its low payload-to-launching-mass ratio. The use of a low-thrust ion-propulsion system would reduce the cost of the mission by a factor ranging from one-third to one-tenth. But the low-thrust ship cannot lift itself against the earth's gravitational field, and is constrained to travel in spirals that are only slightly inclined to the equipotential surfaces. Under such conditions, the exact trajectory cannot be calculated beforehand, and a navigation system must be used that makes new decisions as new data becomes available.

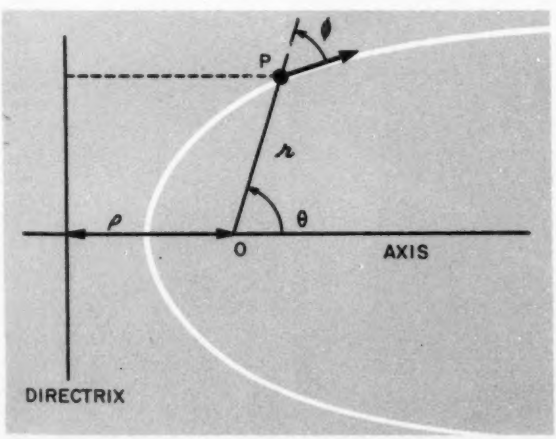


Figure 2

There are four distinct phases of operation for a low-thrust vehicle. The first is the launch or boost phase (Figure 3a), which uses a chemical rocket to place the vehicle in a low orbit in the plane of the ecliptic. The second phase (Figure 3b) might use the thrust of the ion gun applied almost tangentially in order to build up the total energy for escape. Looking at Figure 4, which is a three-dimensional representation of a sector of solar potential with the earth's potential well sunk into the surface, it would appear that considerable care must be taken to avoid sweeping beyond the saddle point between the earth's and the sun's gravitational fields as this would require making a pass near the sun before continuing the journey to the desired destination. If the thrust is programmed to produce an elliptical spiral instead of a circular spiral, as in Figure 3b, the difficulty can be avoided as long as perigee (minimum radius) is toward the sun. The path with respect to the potential energy is shown by the heavy-arrowed line in Figure 4.

As the third phase, or transfer orbit (Figure 3c), is begun, thrust is used to further accelerate the vehicle to reduce the transfer time. Deviations from the desired trajectory may be corrected gradually. Toward midcourse, thrust will be terminated. Further acceleration reduces the transfer time by a negligible amount, since it will soon be necessary to start deceleration to a velocity only somewhat greater than the orbital velocity of Mars. At some time during the transfer it will be necessary to deviate from the plane of the earth's ecliptic and gradually enter the corresponding plane for Mars. As the transfer orbit nears completion, errors in position and velocity become increasingly serious, for with the small amounts of thrust available, error correction takes an appreciable amount of time.

The final phase is to establish a suitable orbit around Mars; this is essentially the second phase in reverse.

For maximum detail in observation, the orbit should dip close to the surface, perhaps less than 100 nautical miles. However, if the orbit is circular, it will mean that a major portion of the escape velocity needed for a return trip has been lost. If a highly eccentric orbit is used, the energy will remain high but the period will be long and, hence, the intervals of observation short and infrequent. Obviously, some practical compromise must be made. It has often been suggested that it would be desirable to rendezvous with one of the satellites of Mars, since this would provide a stable platform for observation without excessive energy loss.

Navigational Devices

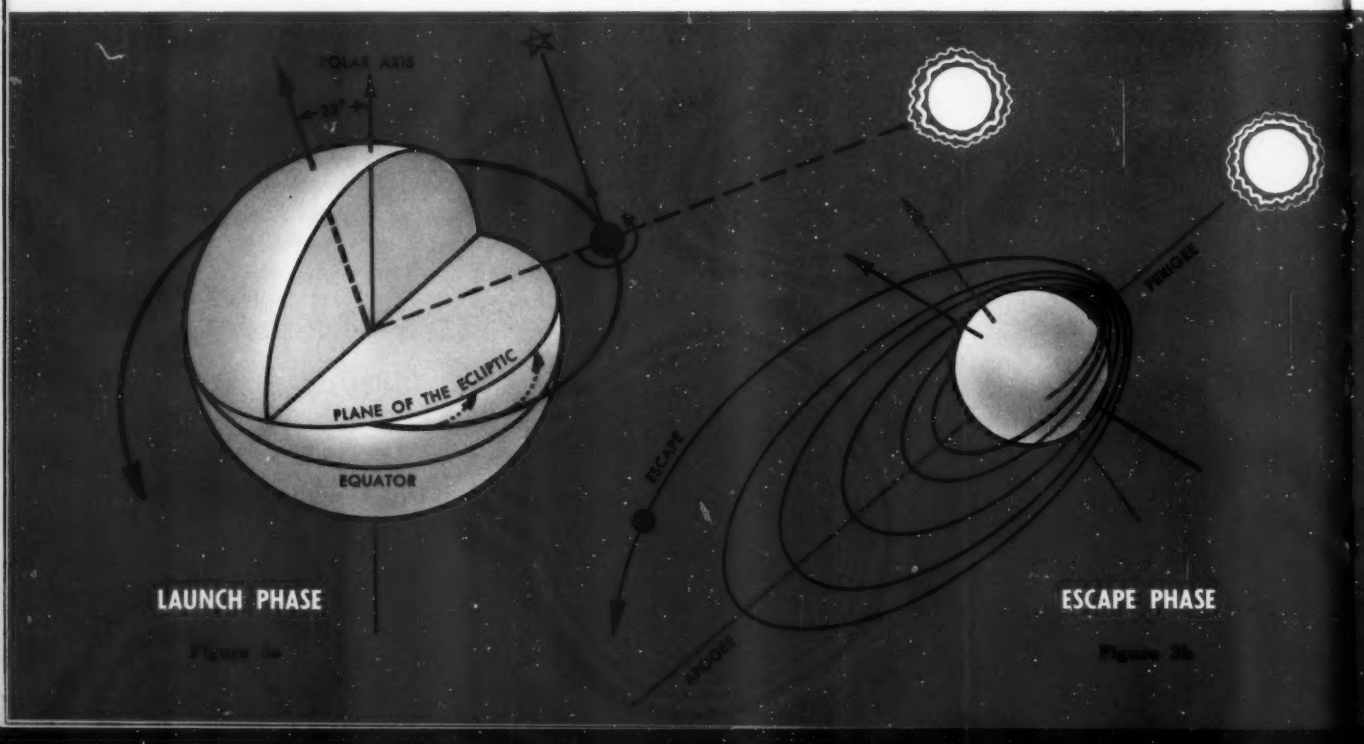
Before discussing the navigational methods that would be used on specified phases of the trip, it will be instructive to consider in some detail the navigational devices, the principles on which they work, the kind of information they provide, and their more important sources of error. Because of their general application to earth-bound navigation, the more familiar inertial devices will not be considered.

Star Trackers

The star tracker is an electro-optical system capable of keeping its optical axis pointed in the direction of a star, provided that the supporting platform's motion is sufficiently well behaved. In the present case we will assume that as a result of short-term inertial guidance the tracker is already pointing at the proper star. Star trackers provide a reference direction such as a normal to a plane, or when the direction is referred to the sun, a cone of position. It should be appreciated that the angles between stars yield no information since the stars are, essentially, points at infinity. Observation of two appropriately chosen stars with respect to the sun, however, will result in two lines of position at the intersection of the two resulting cones of position (Figure 5). The observation of a third star will remove the ambiguity resulting from the two lines of position, but observation of additional stars will yield only redundant information. Parallax corrections may have to be made in the case of the nearer stars. A knowledge of the star's proper motions (which may amount to 10 microradians a year) will be required, in order to provide the extreme accuracy needed. The positions of the stars should be given in terms of the ecliptic, rather than in terms of the earth's equatorial plane in which they are observed. For a moving observer, the apparent position of the star is shifted through an angle $\theta = \tan^{-1} v/c$, by the component v of the observer's velocity perpendicular to the rays of light which travel at the velocity c. For an accuracy of one microradian it is necessary to know the observer's velocity to within about 1000 feet per second.

Sun's Disk Trackers

The sun's disk tracker keeps its optical system centered on the solar disk. Within the solar system the disk will appear to have a finite size. The direction of the sun may be determined by the tracker through the process of bisecting the angle subtended by the disk. A useful estimate of the distance from the sun



may be obtained by either measurement of the apparent disk diameter or by measurement of the radiant energy density. Errors in distance at the earth's orbital radius are predicted to be of the order of from one to ten earth diameters, the larger error being in part due to changes in solar activity, which are estimated to be as high as 0.5 per cent. The addition of a spectroscope to the sun tracker to measure doppler shift would make it possible to estimate the component of vehicle velocity in a radial direction from the sun. To determine the velocity to an accuracy of 1,000 feet per second, it would be necessary to resolve a 3,000 angstrom spectral line to 0.003 angstrom, which would require an appreciable integration time. During the midcourse phase, when velocity is not changing too rapidly, integration time would not be critical. A knowledge of velocity to only the nearest 1,000 feet per second would not provide useful distance information for a trip lasting 10^7 seconds unless the errors could be expected to average out.

Planetary Disk Trackers

The edge of the planet's disk may be tracked or scanned by essentially the same tracker as used for the sun, except that it should respond only to the long-wavelength infrared region corresponding to blackbody radiation at 200°K or less. Otherwise the tracker might follow a crescent-shaped patch of reflected solar energy. Although the earth's shroud of gas tends to render the edge of the disk indistinct, commercially available trackers bisect the disk to an accuracy of about one milliradian. If the angle subtended by the disk is measured to one milliradian, for distances of 10 earth diameters the error in distance would be about 1 per cent. While the surface of Mars shows a wide temperature variation, the lack of atmosphere should be an advantage, and it seems likely that an earth's disk tracker could be made that would also track the Martian disk. Besides supplying the all-important local vertical and distance information, the planetary disk tracker may be used with star trackers to obtain lines of position passing through the planet. For these lines of position to be most useful, an exact knowledge of time and planetary proper motion is required.

Accelerometers

Recent studies have indicated that a measurement of the second space derivative of gravitational potential will, in principle, provide an indication of the distance (r) from a known gravitational mass. A simple accelerometer measures only the first space derivative of gravitational potential, and when located at the center of mass of a vehicle in free fall, reads zero. However, sensitive accelerometers located within the vehicle but nearer or further from the attracting body would give acceleration readings slightly different from zero. While neither of the readings are the true accelerations at those points, the difference in the readings, Δa, divided by the separation distance, Δr, gives the second space derivative of gravitational potential (Figure 6). The principles may be expressed by the following equations.

$$U = -\frac{GM}{r} \qquad \text{Gravitational Potential}$$

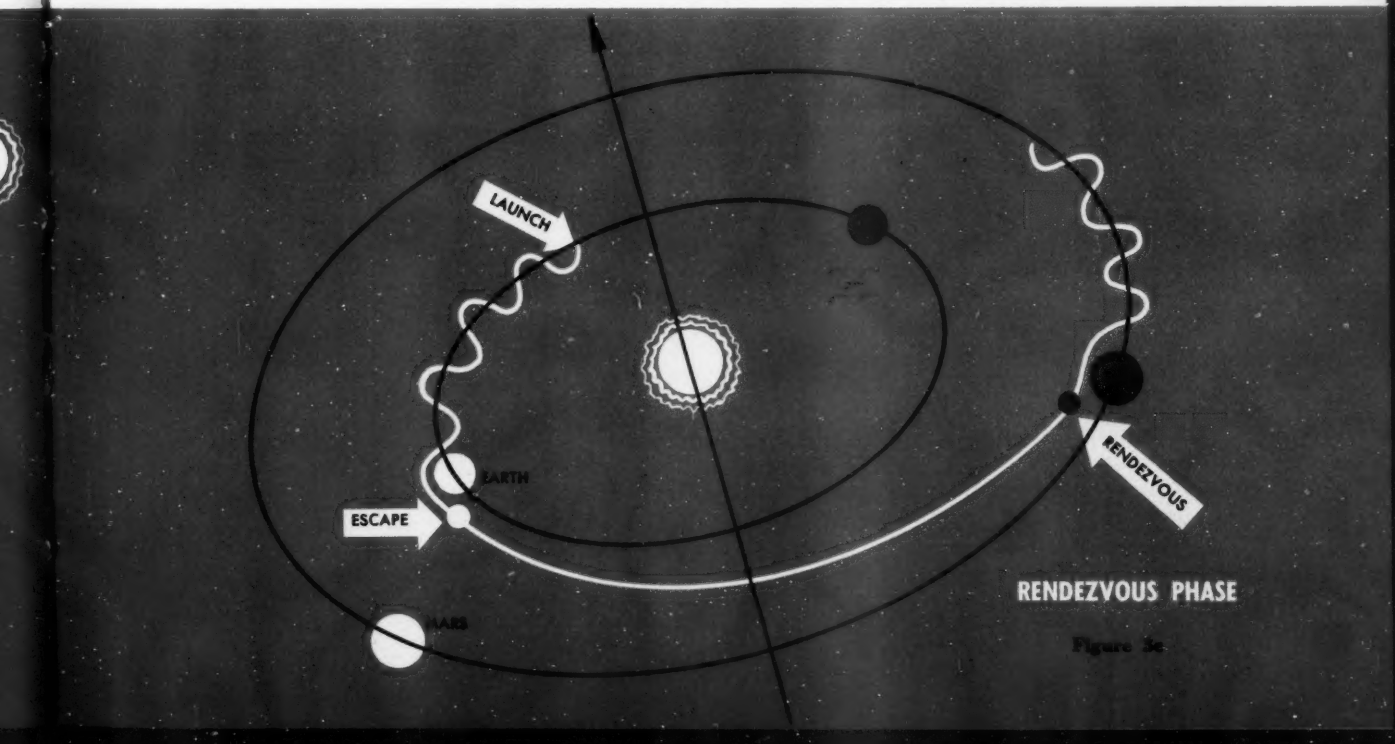


Figure 5c

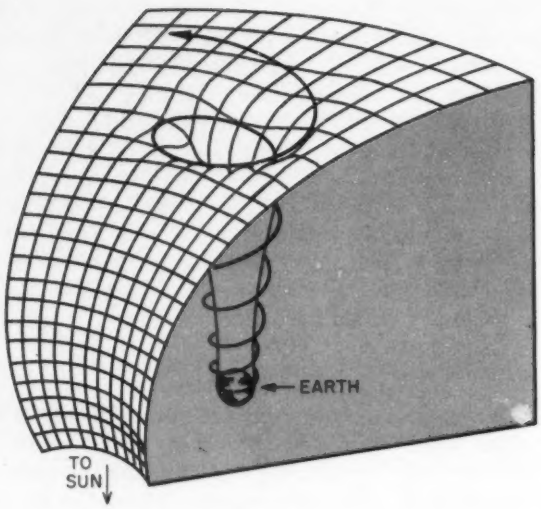


Figure 4

$$\frac{dU}{dr} = \frac{GM}{r^2}$$ Gravitational Field (first derivative)

$$\frac{d^2U}{dr^2} = -\frac{2GM}{r^3}$$ Second Derivative

$$\frac{d^2U}{dr^2} = \lim_{\Delta r \to 0} \frac{\Delta a}{\Delta r} \doteq \frac{\Delta a}{\Delta r}$$

Since all of the quantities are either known or measured the equations may be solved for r:

$$r = \left[2GM\left(\frac{\Delta r}{\Delta a}\right)\right]^{1/3}$$

In practice the direction of the maximum value of the second derivative could be obtained, giving the local vertical. Some of the practical problems of such a device would involve suitable distribution of the vehicle's mass and the extreme sensitivity required of the accelerometers. It should be emphasized that these results are independent of whether the vehicle is under propulsion, in free fall, or even gyrating wildly.

Radar

The role that radar will play in space navigation is likely to change drastically with time. It has been proposed that a high power transmitter, large antenna, and sensitive receiver on the earth, and a small transponder on the vehicle, together with a command guidance system, might provide midcourse guidance to the nearer planets. One difficulty with such a system is that it provides only one component of the vehicle's velocity. An active Doppler radar is likely to be used for terminal guidance on very close approaches to a planetary surface, especially in the case of Venus where the surface is obscured to optical wavelengths. Such a radar (or radar altimeter) will certainly be used for a soft landing. Although it is generally assumed that any active radar on space vehicles will be a short-range device, it is possible to divert many kilowatts or megawatts from the propulsion power source for radar use during short intervals. It is also frequently assumed that antennas will be small, but actually a lightweight folding antenna of the order of hundreds of feet in diameter is possible if it is made stowable for launch. This follows from the fact that a low-thrust vehicle is either in free fall with no forces on the structure, or it is under propulsion with a force equivalent to 10^{-4} g. In other words, in space the antenna is 10^4 times as "strong" as it was on earth. Eventually large radar stations located on the planets may provide for sighting, computation, and command guidance during the entire trip. Alternately, Loran stations may be set up on planets and space buoys.

The mathematician Lagrange was the first to explain a particular solution for the three-body problem as indicating the existence of stable points in space. One such point would be located at the third vertex of an equilateral triangle, with the sun and a planet at the other vertices. At least 12 asteroids, known as the Trojan Group, have been found in such a stable configuration with respect to the sun and Jupiter (Figure 7). Similar positions with respect to the sun and other planets, or the moons of a planet and the planet itself, would provide excellent stations for navigational space buoys.

The meteor collision problem does not seem to be solvable by the use of radar. A meteor less than a

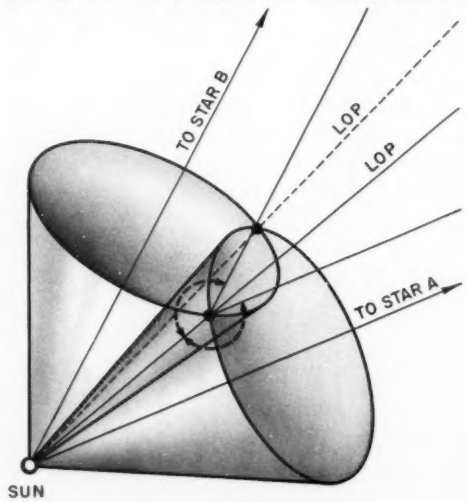


Figure 5

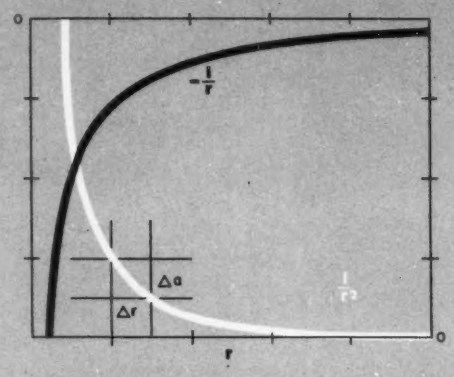


Figure 6

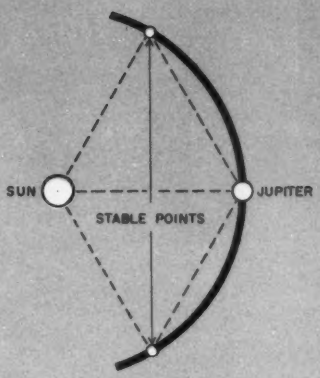


Figure 7

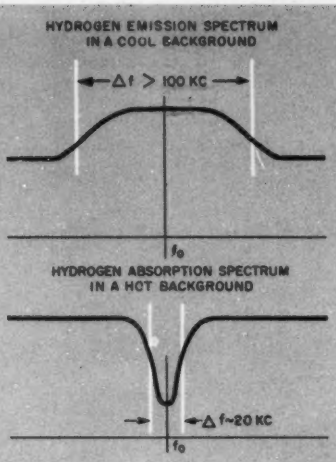


Figure 8

centimeter in diameter is capable of inflicting mortal damage to a light space vehicle, yet it would have to be detected, and its course determined, while some 300 to 3,000 miles away (depending on its relative velocity, 10 to 100 km/sec). The required long range is a result of the small acceleration (10^{-3} meters/sec^2) available from the ion-propulsion system to alter the collision course. Actually some higher-thrust emergency device might be used to avoid collisions in manned vehicles.

Space Radiation Devices

Neutral hydrogen atoms in their ground state produce a characteristic radiation at 1420 mc (microwave region). When observed against a cooler background, an interstellar hydrogen cloud will exhibit an emission spectrum in the vicinity of 1420 mc. When observed against a hotter background such as a radio "star," an absorption notch will be seen (Figure 8). The emission spectrum is in general several hundred kilocycles in width, while the notch may be as narrow as 20 kilocycles. Because it is narrow in width and appears in a particular direction (radio "star"), and is thus identifiable with previously cataloged information, the notch will probably be more useful than the emission spectrum. The frequency shifts due to the relative velocity between the hydrogen clouds and the earth have been measured. If a suitable catalog were made it would be possible to determine the component of the vehicle's velocity in a given direction merely by measuring the Doppler shift of the absorption line. The scheme is somewhat more easily implemented as a result of our present understanding of correlation and signal detection in a noise background, based on microwave radar receiver experience. The major advantage lies in the low power consumption of an entirely passive system.

Particle Density

When more is known about space it may be possible to use other radiation or particle sources for navigation. For example, certain classes of ionic particles may come from specific directions, or may constitute radial marker bands around the sun. The density of gas clouds and charged particles may be as useful as the water depths to a fog-bound mariner. However, the low accuracy of such methods would probably limit their use to emergency situations, after more precise equipment had been damaged.

It seems unlikely that magnetic fields will serve a useful purpose in navigation except possibly to help the vehicle avoid paths through high densities of charged particles. The configuration of the earth's magnetic field is such that it does not provide any valuable information for space travel.

Thrust Measurement

If the initial mass of the vehicle and the amount of mass expelled are known, then it is possible to predict the acceleration from a measurement of the ion gun thrust. It may be necessary to control or program the thrust level to ensure a certain course. The measurement of thrust will also be required as a cross check against power consumption to determine proper gun operation.

Conclusion

The problems that seem formidable today appear so largely because navigation techniques are still in their infancy. As these techniques mature, the outlook which has been presented here may someday appear almost as primitive as that of the cave man. The advent of the space age assures us of the continued discovery of new frontiers and new problems to challenge man's curiosity and creative desire.

Raytheon Flight-Tracker radar, showing air routes near Indianapolis. Straight lines show routes, X's are check points, concentric circles indicate range in miles. "Pips" are aircraft.

New Raytheon radar helps safeguard <u>your</u> flight

Commercial, private and military flights total 69,000 a day in the U.S.! Control of this traffic, the task of the Federal Aviation Agency, is now aided by Raytheon Flight-Tracker radars. Each of these powerful units can pinpoint aircraft up to 200 miles away in all weather—even in storms.

Raytheon has delivered 26 radars for a system to span the continent—to be fully operational by Fall, 1959. The control network will eventually blanket the entire country with 70 radars. Plans also call for the incorporation of a unique microwave tube, the Raytheon *Amplitron*, in the Flight-Trackers to increase their range and tracking efficiency.

By helping the F.A.A. to control airways traffic, speed schedules and reduce "stacking," Raytheon brings nearer the solution of a major transportation problem.

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